

Wood Moisture Content Measurement by X-Ray Exposure Method

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ABSTRACT Although quite a number of papers can be found up to now dealing with the subject of the measurement of wood density by using the X-ray exposure methods, direct scanning or radiographic photography, the following two aspects, which are very important from both theoretical and engineering application points of view, have not yet been properly handled. One is that the elementary analyses or the experimental measurement on the mass attenuation coefficients were not specified in regard to spectrum energy distributions^[1]. In this connection, the ambiguities in the specification of the coefficients and in turn for the results among studies arise when only one of the two parameters, namely wave length and applied voltage, of defining the energy spectrum of X-ray is given. The other is that the relationships between the relative intensity and the sample thickness as well the wood moisture content^[2], which are the critical factors for the design and the selection of X-ray apparatus, were not sufficiently examined. In addition, the knowledge of the measurement of wood moisture content by using the direct X-ray scanning method is also almost unavailable now. In the study, the direct X-ray scanning method of measuring wood moisture content was at first investigated theoretically with respect to the relationship between the mass attenuation coefficients of wood (beech, *Fagus Sylvatica*) and the maximum spectrum energy of X-ray. Secondly, the dependence of the relative intensity on the sample thickness and on the wood moisture content was analysed. The main advantage of the method is on-site nondestructive measuring of wood moisture content in the processes such as drying, impregnation and unsteady mass diffusion. Specifically for the application in the area of biomechanics, the method can also be used for understanding the water pathway within wood, for example, the water around the knots and the relation between the stress distribution and the local moisture content of wood.

Key words: Mass attenuation coefficient, Maximum spectrum energy, Moisture content, Relative intensity, Sample thickness, X-ray exposure

INTRODUCTION

The on-site non-destructive measurement of wood moisture content attracts great interests. It plays important parts in the scientific research such as on the heat and mass transport processes in wood drying, the impregnation of liquid in wood, the moisture content distribution in relation to the local stress development and the detection of the defects in wood. In the engineering applications, it facilitates the means of the auto-control of drying kilns in the lumber drying process. Specifically for the applications in the area of biomechanics, the method can also be used for understanding the water pathway within wood, for example, the water around the knots.

Although quite a number of papers can be found up to now in dealing with subject of the measurement of wood density by using the X-ray exposure methods, direct scanning or radiographic photography, the following two aspects, which are very important from both the theoretical and the engineering application points of view, have not yet been properly handled. One is that the

elementary analyses or the experimental measurement on the mass attenuation coefficient were not specified in regard to their spectrum energy distribution^[1]. In this connection, the ambiguities in the specification of the coefficients and in turn for the results among studies arise when only one of the two parameters, namely wave length and applied voltage, of defining the energy spectrum of X-ray is given. The other is that the relationships between the relative intensity and the sample thickness as well the wood moisture content^[2], which are the critical factors for the design and the selection of X-ray apparatus, were not sufficiently examined. In addition, the knowledge of the measurement of wood moisture content by using the direct X-ray scanning method is also almost unavailable now.

In the study, the direct X-ray scanning method of measuring wood moisture content was at first investigated theoretically with respect to the relationship between the mass attenuation coefficients of wood (beech, *Fagus Sylvatica*) and the maximum spectrum energy of X-ray. Secondly, the dependence of the relative intensity on the sample thickness and on the wood moisture con-

tent was analysed. The theory was discussed by comparing with the experiments made on green wood (both sap wood and heart wood).

The possibilities of measuring wood moisture content and density at the same time by applying two exposure sources in different voltages or wavelengths or different combinations of the two parameters were also investigated. If sample thickness, relative value of intensities and mass attenuations of H_2O and wood are known, the density and the moisture content of wood may be determined by using the direct scanning procedure.

The calibration of measuring wood moisture content by using a linear X-ray detector was made.

THEORY AND METHOD

The Relative Intensity at the Maximum Spectrum Energy of X-ray The relative intensity at the maximum spectrum energy of X-ray is calculated in accordance to:

$$I/I_0 = \exp(-\mu_l \cdot t) = \exp(-M_a(w_h) \cdot \rho_d \cdot t) \quad (1)$$

where I is the accidental X-ray intensity, Counts; I_0 is the diminished X-ray intensity after the absorption of the exposed media, counts; $\mu_l = M_a(w_h) \cdot \rho_d$, the linear attenuation coefficient of the absorber, $1/\text{cm}$; ρ_d is the density of wood, g/cm^3 and t is the sample thickness of wood, cm. For over dry wood, the applied data are $\rho_d = 0.66 \text{ g}/\text{cm}^3$, $t = 0.2, 0.4, 0.6, \dots, 7.2$ cm and $M_a(w_h) = 0.32 \text{ cm}^2/\text{g} - 1661.92 \text{ cm}^2/\text{g}$.

The Dependence of the Relative Intensity of X-Ray Exposure on the Thickness of Wood Sample In the calculation, the linear attenuation coefficient, μ_l was kept as constant. The results are shown in Fig. 1 and Fig. 2.

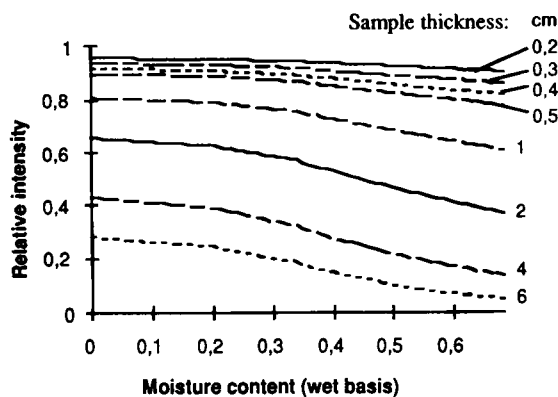


Fig. 1. Relative intensity versus wood moisture content (beech, $\rho = 0.66 \text{ g}/\text{cm}^3$ for over-dry wood) for different sample thickness at the maximum spectrum energy of x-ray for the applied voltage 50 kV

The Dependence of the Relative Intensity of X-

ray Exposure on Wood Moisture Where the variation of wood moisture content is considered, the relative intensity of X-ray exposure is defined as:

$$I/I_0 = \exp(-\mu_l \cdot t) = \exp(-M_a(w_h + H_2O) \cdot \rho_w \cdot t) \quad (2)$$

where

$$M_a(w_h + H_2O) = M_{cw} \cdot M_a(w_h) + (1 - M_{cw}) \cdot M_a(H_2O),$$

the attenuation coefficient of moist wood, cm^2/g ; ρ_w is the density of moist wood, g/cm^3 and M_{cw} is the wood moisture content in wet basis, which is defined as

$$M_{cw} = \frac{\text{weight of moist wood} - \text{Weight of dry wood}}{\text{weight of dry wood}} \quad (3)$$

The Linearization equations of the curve of wood density versus wood moisture content (Bild 6, Brummer-Hildebrabd, and the text book of WOOD DRYING) are listed in Table 1.

Table 1. The linearization equations of wood density versus wood moisture content

i	$M_{cd}, \%$	$M_{cw}, \%$	Linearization equations of $\rho_{w_i} f(M_{cw})$
1	0-25	0-20	$\rho_{w1} = \rho_d + 0.25 M_{cw1}$
2	25-50	20-33.33	$\rho_{w2} = 0.83 + 1.6644(M_{cw2} - 0.2)$
3	50-125	33.33-55.56	$\rho_{w3} = 0.83 + 1.6644(M_{cw3} - 0.3333)$

In the Table 1, i is the steps of the linearization; ρ_w is the over dry density of wood, g/cm^3 M_{cd} is the wood moisture content in dry basis; ρ_{w1} is the density of moist wood when $0 \leq M_{cd1} \leq 0.2$, g/cm^3 ; ρ_{w2} is the density of moist wood when $0.2 \leq M_{cd2} \leq 0.3333$, g/cm^3 and ρ_{w3} is the density of moist wood when $0.3333 \leq M_{cd3} \leq 0.5556$, g/cm^3 .

The Dependence of the Relative Intensity of X-Ray Exposure on the Applied Voltage and the Wave Length

The results are shown in Fig. 2

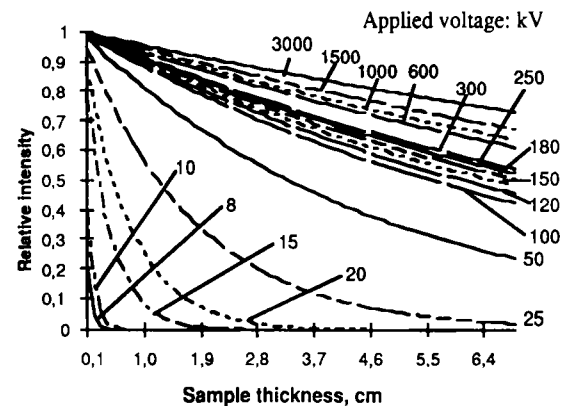


Fig. 2. Relative intensity versus sample thickness (beech, over-dry wood, $\rho = 0.66 \text{ g}/\text{cm}^3$) for different applied voltage at the maximum spectrum energy

The energy spectrum of X-ray as a function of applied voltage and wave length is calculated in according to Plank's law:

$$E_{h\lambda}(\lambda, I) = C_1 / [\lambda^5 (e^{C_2 / (\lambda T)} - 1)] \quad (4)$$

where: $E_{b\lambda}(\lambda, V)$ is the absorptive spectrum energy of black body as a function of the applied voltage and the wavelength, W/m^3 ; V is the applied voltage, V ; λ is the wavelength, m ; C_1 is constant depending on the Plank-Borczemane constats and C_2 is constant depending on the applied voltage and the wavelength. The relative spectrum energy of X-ray is calculated from:

$$\xi = E_{b\lambda}(\lambda, V) / E_{b\lambda_{\max}}(\lambda_{\max}, V) \quad (5)$$

where ξ is the relative spectrum energy of X-ray in relation to the maximum spectrum energy distribution: $E_{b\lambda_{\max}} = 12.87 \times 10^{-6} T$, the maximum spectrum energy, W/m^3 , in which T is temperature, K and

$$\lambda_{\max} = 2.898 / T = 2.898 \times 10^{-3} / T \quad (6)$$

which is the wave length which generates the maximum spectrum energy of X-ray for a given applied voltage, m . The concerned constants are determined by taking the applied voltage in analogy to the potential of temperature in thermal radiation as specified in Plank's law. In case of the potential of applied voltage in X-ray radiation, it is known that :

$$\lambda_{\max} = 1.5 \times 12400 / V \times 10^{-10} = 1.86 \times 10^{-8} / V \quad (7)$$

and for $V=50$ kV, $\lambda_{\max} = 3.72 \times 10^{-8} m$ is obtained. By substituting the value of λ_{\max} into the equation (3), the corresponding temperature is to be $7.79 \times 10^4 K$ and finally we have

$$V / T = 50 \times 10^3 / (7.79 \times 10^4) = 0.6418, V / K^0 \quad (8)$$

Because the constant C_1 will be eliminated in the calculation of the value of the relative intensity, it is therefore not bothered to determining it under the circumstance. For the given $C_2 = m \cdot K$ for thermal radiation, it follows from

$$C_2 = [C_2 / (\lambda_{\max} \cdot T)] \cdot (\lambda_{\max} \cdot T) = (C_2 / T) / T = 14.388 \times 10^{-3} \times 0.6418 = 92.34 \times 10^{-4}, m \cdot kV \quad (9)$$

The maximum relative spectrum energy distribution in relation to the corresponding wave length and the applied voltage are given in Table 3.

EXPEREMENTS AND RESULTS

The Chemical Compositions of Beech

The elementary analyses on the mass attenuation coefficients of wood and water as well their relations were made based on the chemical compositions of beech (Table 2). They were evaluated on the average of sapwood and heartwood.

The mass attenuation coefficients of beech was consequently made in accordance to the equation:

$$M_a(w_b) = \sum_{i=1}^4 \beta_i M_m = 48.50\% \times M_{oc} + 44.97\% \times M_{on} + 6.30\% \times M_{oh} + 0.23\% \times M_{nn} \quad (10)$$

Table 2. Chemical compositions of beech for the elementary analysis of the mass attenuation coefficients of X-ray

Chemica composition	Autom number	Autom weight	Percentage by weight, %
Carbon	6	12.0110	48.50
Oxygen	8	15.9994	44.97
Hydrogn	1	1.0080	6.30
Nitrogen	7	14.0067	0.23
Σ			100

where $M_a(w_b)$ is the mass attenuation coefficient of beech wood, cm^2/g ; β_i are the percentages by weight for each chemical component of wood, $i=1,2,3$ and 4 for oxygen, carbon, hydrogen and nitrogen respectively; M_m 's are the mass attenuation coefficient of the i 'th chemical component, cm^2/g and $\Sigma \beta_i = 1$ is the sum of the weight percentages of the chemical component of water. The elementary calculation of the mass attenuation coefficient of water was made in accordance to the equation:

$$M_a(H_2O) = \sum_{i=1}^2 \beta_i M_m = 88.81\% M_{oc} + 11.19\% M_{oh} \quad (11)$$

where $M_a(H_2O)$ is the mass attenuation coefficient of water, cm^2/g ; β_i 's are the percentages by weight for each chemical component of water, $i=1$ and 2 for oxygen and hydrogen respectively; M_m 's are the mass attenuation coefficients of the i 'th chemical component, cm^2/g and $\Sigma \beta_i = 1$ is the sum of the weight percentages of the chemical components of water

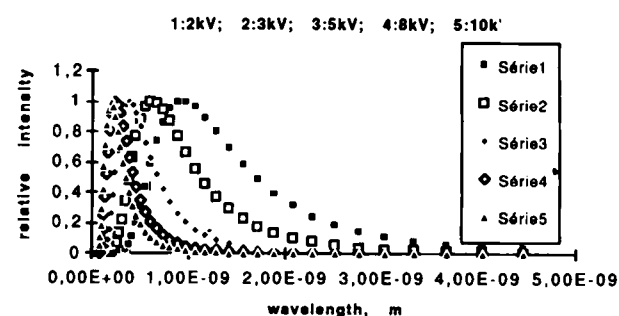


Fig. 3. The relative intensity spectrum

The mass attenuation coefficients of oxygen from the wave length of $0.005 \leq \lambda \leq 0.064 \text{ \AA}$ are interpolated values. The wave length of $\lambda = 0.146 \text{ \AA}$ was included in the estimation of the change rates of the mass attenuation coefficients of oxygen to the wave length. The linear equation ($0.005 \text{ \AA} \leq \lambda \leq 0.064 \text{ \AA}$) was used in the interpolation procedure.

Table 3. Results of the elementary analyses on the mass attenuation coefficient of wood and water as well the displacement at the maximum spectrum energy

$\lambda, \text{\AA}$	V, kV	E_p, keV	C	M_{air}, H	$\text{cm}^2/\text{g O}$	N	$M_A(w_b), \text{cm}^2/\text{g}$	$M_A(\text{H}_2\text{O}), \text{cm}^2/\text{g}$	$\Psi, \text{cm}^2/\text{g}$	$\lambda_{\text{max}}, \text{\AA}$
44.60			2170		5765	3850	3654	5112	71.37	
9.870	2	1.22	1063		2540	1796	1662	2256	73.67	19400
8.320			656.0		1585	1109	1034	1048	73.42	
6.970			390.0		976.0	645.0	629.54	866.80	72.63	
6.390	3	1.83	185.0		476.0	312.0	304.50	422.70	72.03	18060
517.0			160.0		413.0	273.0	263.95	366.79	71.96	
4.360			97.80		258.0	166.0	163.84	229.13	71.50	
4.150			84.60		222.0	144.0	141.20	197.16	71.62	
3.930	5	3.04	71.00		189.0	121.0	119.70	167.85	71.32	18700
3.590			55.20		150.0	96.00	94.450	133.22	70.90	
3.380			46.00		117.0	79.50	75.110	103.91	72.28	
3.030			35.00		84.00		54.750	74.600	73.39	
2.740			25.00		60.00		39.110	53.290	73.39	
2.500			17.80	0.520	44.50		28.680	39.580	72.46	
2.290	8	4.87	15.00		36.40		23.640	32.33	73.14	
1.930	10	6.08	8.750	0.500	21.70	14.00	14.070	19.330	72.78	19200
1.539			4.520	0.480	11.10	7.450	7.230	9.910	72.96	
1.389			3.350	0.470	8.100	5.500	5.310	7.250	73.27	
1.235	15	9.13	2.420	0.460	5.700	3.950	3.870	5.110	73.82	17850
1.000	20	12.17	1.360	0.450	3.130	2.100	2.100	2.83	74.21	18800
0.880			0.990	0.440	2.200	1.500	1.500	2.000	74.92	
0.710	25	15.21	0.598	0.435	1.220	0.870	0.868	1.132	76.67	18500
0.631			0.467	0.435	0.900	0.610	0.660	0.848	77.84	
0.497			0.315	0.435	0.520	0.040	0.415	0.511	81.28	
0.476			0.304	0.430	0.485		0.393	0.479	82.00	
0.417	50	30.42	0.256	0.390	0.372	0.310	0.317	0.374	84.68	19000
0.260			0.185	0.385	0.210	0.200	0.209	0.230	90.98	
0.200			0.175	0.375	0.183	0.180	0.191	0.205	93.51	
0.195	100	60.83					0.191	0.204	93.63	19500
0.175			0.163	0.360	0.169	0.166	0.178	0.190	93.56	
0.161	120	73.00	0.159	0.350	0.166	0.165	0.174	0.187	93.15	19320
0.146			0.155	0.340	0.162		0.170	0.182	93.14	
0.130			0.152	0.320	0.157		0.165	0.175	93.86	
0.120	150	91.25	0.150	0.315	0.154		0.162	0.172	94.09	18150
0.113			0.147	0.310	0.153		0.160	0.159	93.59	
0.098	180	109.5	0.142	0.280	0.144		0.151	0.150	95.01	18000
0.072	250	152.1	0.136	0.250	0.137		0.143	0.143	95.77	18000
0.064	300	182.5	0.130	0.245	0.130		0.137	0.134	95.86	19200
0.050			0.120	0.225	0.123		0.128	0.129	95.50	
0.040			0.110	0.205	0.119		0.120	0.121	93.00	
0.030	600	365.0	0.095	0.180	0.114		0.109	0.117	90.10	18000
0.024	1000	608.3	0.080	0.165	0.111		0.100	0.108	85.50	24000
0.010	1500	912.5	0.059	0.117	0.107		0.088	0.099	81.50	15000
0.005	3000	1825	0.039	0.078	0.102		0.070		70.70	15000

$$(\lambda_i - \lambda_{i-1}) / (0.13 - M_{\text{air}, i+1}) = 2.13 \quad (12) \quad M_{\text{air}, i+1} \text{ 's are the mass attenuation coefficients of oxygen}$$

where λ_i 's are the wave lengths for $i=1,2,3,\dots,n$, \AA ; at λ_{i+1} , cm^2/g and 2.13 is the estimated slop for 0.064 \AA

$\leq \lambda \leq 0.146 \text{ \AA}$ and for $0.13 \text{ cm}^2/\text{g} \leq M_{ao} \leq 0.162 \text{ cm}^2/\text{g}$.

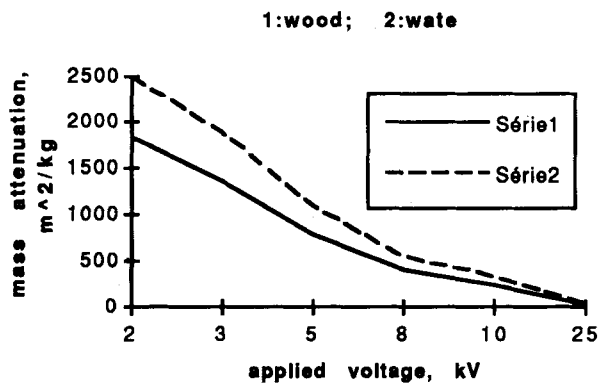


Fig. 4. The weighted means of mass attenuations of wood and water on wavelength versus applied voltage

The Results of the Elementary Analyses

The mass attenuation coefficients of wood and water, the displacements and the ratios of the mass attenuation coefficients of wood to those of water given at the maximum speculum energy of X-ray are shown in Table 3.

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